Cavity-enhanced Ion-Ion Remote Entanglement

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• Ion-ion remote entanglement

• Cavity-enhanced Raman transition

• Noise process and temporal property of photons

• Result:
  • Optimising cavity parameters
  • Technical challenge
Ion-ion remote entanglement

- Quantum entanglement is the central resource behind quantum information science
Ion-ion remote entanglement

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- Ion trap is advantageous for quantum information processing

- Local qubit entanglement is confronted with practical limits to the number of qubits that can be reliably controlled
Two main approach to achieve remote entanglement:

1. Move qubits between modules[1]

Ion-ion remote entanglement

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   - Low entangling rate (5Hz) when photons are collected by lens. [2]
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   - Photon collected by cavity
     a) Direct excitation
     b) Raman transition

Cavity-enhanced Raman transition

Direct excitation

\[ |0\rangle \xrightarrow{\sigma} |1\rangle \]
\[ |0\rangle \xrightarrow{\pi} |1\rangle \]
\[ \pi \text{ pulse} \]

Cavity-enhanced Raman transition

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\[ |1\rangle \xrightarrow{\pi} |0\rangle \]
\[ \pi \rightarrow V \]
\[ \sigma \rightarrow H \]
Cavity-enhanced Raman transition

Direct excitation

\[ |0\rangle \rightarrow |\pi\rangle \rightarrow |\sigma\rangle \rightarrow |0\rangle \]

Cavity-enhanced Raman transition

\[ |1\rangle \rightarrow |\pi\rangle \rightarrow |\sigma\rangle \rightarrow |1\rangle \]

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Hamiltonian

\[ H_{\text{int}} = \hbar g_H e^{i \Delta_H} \sigma_0 a_H^+ + \hbar \frac{\Omega_H}{2} e^{-i \Delta_H} \sigma_{u1} e + \hbar g_V e^{i \Delta_V} \sigma_1 a_V^+ + \hbar \frac{\Omega_V}{2} e^{-i \Delta_V} \sigma_{u1} e + c.c. \]

Advantage:

- Flexible choice of frequency,
- Continuous driving laser,
- Controllable photon wave packet.
Noise process:

\[ |u\rangle \quad \rightarrow \quad |1\rangle \quad \rightarrow \quad |0\rangle \]

\[ |e\rangle \quad \rightarrow \quad |\pi\rangle \quad \rightarrow \quad |\sigma\rangle \]
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- Loss channel:

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  \text{infidelity} \approx \frac{2\kappa^2}{\Delta_H^2 + \Delta_V^2}
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Two time correlation function:

\[ f(t, t') = \langle \hat{E}^+(t) \hat{E}(t') \rangle \]
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Temporal mode mixing for double Λ system:

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\tilde{f}(t, t') = \begin{bmatrix}
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Noise process and temporal property of photons

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\]

\[
\lambda_0 = 0.94, \quad \lambda_1 = 0.035, \quad \lambda_2 = 0.011, \quad \lambda_3 = 0.0047
\]

\[
\sigma, \quad \pi
\]

|e⟩ → |u⟩ → |1⟩

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Cavity geometries, excitation lasers, B, detectors. Fabrication precision...
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• Optimising transmission, concentricity, and detection window

$L = 400\mu m, D_{\text{mirror}} = 100\mu m, loss = 10\text{ ppm}, B = 100G, misalignment = 700\text{ nm}, \tau_{\text{prep}} = 0.5\mu s, \eta = 0.5$
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  - Cavity geometries, excitation lasers, B, detectors, Fabrication precision...
  - Optimising transmission, concentricity, and detection window

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Technical challenges

• Best ion-ion entanglement performance with fabrication errors.
Summary and outlook

Summary

• A solver to predict and optimise ion-ion remote entanglement regarding temporal mixing and Loss channel
• >100KHz Bell state rate and >98% fidelity can be achieved by reasonable fabrication errors

Outlook

• Take birefringence into account
• Construct an analytical description
Thank you